TITLE OF THE INVENTION

Interference Suppression in a Spread Spectrum Communications System Using Non-Linear Frequency Domain Excision

CROSS REFERENCE TO RELATED APPLICATIONS

This application claims priority under 35 U.S.C. §119(e) of provisional patent application no. 60/262,499 filed January 18, 2001, the disclosure of which is incorporated by reference herein.

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

--Not Applicable--

BACKGROUND OF THE INVENTION

The present invention is related to the field of interference suppression in wideband communications systems such as spread-spectrum communications systems.

The explosive growth of wireless communications has necessitated new and innovative approaches to assigning and using the fundamentally limited frequency spectrum. One proposed solution is to permit a given spectral band to be shared by two or more user communities that employ different signaling methods, provided the signals produced by one group of users don't materially affect the communications efficacy of the others. One practical method is to allow wideband, spread-spectrum communications to be conducted in the same frequency bands that support narrowband users. In this approach a wideband transmitter spreads its energy over a much larger portion of the allocated band than do the narrowband transmitters. Because a narrowband receiver is sensitive to narrowband signals, it intercepts only a small fraction of the energy transmitted by a

Express Mail Number

EL751777901US

ATTORNEY DOCKET NO. TITAN-001XX
WEINGARTEN, SCHURGIN,
GAGNEBIN & HAYES, LLP
TEL. (617) 542-2290
FAX. (617) 451-0313

wideband user. The effect of this small amount of interference on the narrowband system is commensurately small and generally negligible.

A similar argument does not apply for a spread spectrum user. Because it is sensitive over a wide band, a wideband receiver intercepts all the narrowband signals in its band in addition to the wideband signal of interest. Each of the interfering narrowband signals is received at full energy. Such interfering signals can significantly degrade communications performance by overwhelming the receiver with strong interfering energy and/or by causing transmitter power control algorithms to compensate for the interference by increasing the transmit power level. The latter can have the effect of increasing the level of interference caused to narrowband users by the spread spectrum system, thereby degrading the quality of service for narrowband as well as wideband users.

Frequency domain excision techniques have been used to address the problem of narrowband interference in wideband systems. In frequency domain excision, a Fourier transform is applied to a sampled version of the received baseband communications signal to convert the input time waveform into the frequency domain. The Fourier transform is typically implemented in digital form using the Fast Fourier Transform (FFT) algorithm. Once the frequency domain representation has been generated, the locations of the interfering signals are determined, generally by identifying anomalous peaks in the frequency-domain spectrum. One or another type of non-linear processing is then performed on the spectral coefficients in order to suppress the effects of unwanted narrowband signals. The modified frequency domain coefficients are then transformed back to the time domain using an inverse FFT in order to construct the output signal.

One limitation of such conventional frequency-domain processing is that a narrowband interfering signal generally appears in more than one FFT coefficient, or frequency bin, even

ATTORNEY DOCKET NO. TITAN-001XX
WEINGARTEN, SCHURGIN,
GAGNEBIN & HAYES, LLP
TEL. (617) 542-2290
FAX. (617) 451-0313

though the actual frequency of the interfering signal may be localized to a single bin. This problem arises due to the poor frequency sidelobe structure of the FFT. The excision system eliminates many more FFT coefficients than necessary, resulting in serious degradation of receiver performance despite the removal of the interfering signal.

The usual solution to the frequency sidelobe problem is to apply a multiplicative window to each input block of samples prior to computing the Fourier transform. Specifically, if the N-point window function is denoted $W(n)$ and the input data for the k^{th} block is denoted as $X(k,n)$, then windowed data $X_w(k,n)$ which is used as the input to the Fourier transform is given by $X_w(k,n) = X(k,n) \times W(n)$. Several popular window functions include the Bartlett, Blackman, Chebyshev, Hamming, Hanning and Kaiser windows. All of these have the same general shape, in which they are symmetric about their mid-point and monotonically decrease from their largest value at the center, to zero or near-zero at the end points. Depending on which window is used, varying amounts of sidelobe suppression can be achieved in exchange for somewhat reduced frequency resolution.

Although the application of an input window reduces or eliminates the sidelobe problem and facilitates removal of only those frequency bins that truly contain interfering signals, it also introduces distortion into the reconstructed time sequence produced by the inverse Fourier transform. This distortion affects the performance of the downstream receiver demodulator. Several techniques have been suggested for mitigating window-induced distortion, such as the use of adaptive, time-varying demodulation techniques and the use of transforms other than the Fourier transform. These techniques suffer from computational complexity and relatively high cost.

One key aspect of excision performance is the estimation of appropriate thresholds that are used to distinguish desirable signals from interfering signals. Currently, various sliding

ATTORNEY DOCKET NO. TITAN-001XX
WEINGARTEN, SCHURGIN,
GAGNEBIN & HAYES, LLP
TEL. (617) 542-2290
FAX. (617) 451-0313

window averages and median filtering techniques are used. In addition to being computationally costly, the performance of many of these methods degrades significantly in the presence of large numbers of interfering signals. Additionally, many excision techniques require the use of specialized demodulation logic in the receiver, resulting in added cost, complexity and power consumption.

BRIEF SUMMARY OF THE INVENTION

In accordance with the present invention, methods and apparatus are disclosed for interference suppression in a wideband, spread-spectrum receiver. An essentially arbitrary number of simultaneous narrowband signals of different amplitudes and frequencies can be excised without materially degrading the performance of the wideband receiver. The interference suppression technique can be used to enable successful implementation of the above-described spectrum sharing strategy.

In the disclosed technique, a window function is applied to each of overlapped blocks of received signal samples. The window function has a central maximum and tapers to zero at beginning and ending points. A transform function is performed on the windowed blocks to generate corresponding blocks of frequency-domain coefficients.

Each block of frequency-domain coefficients is morphologically filtered to generate a threshold function for the block which represents an estimate of the spectrum of the desired wideband signal component. The threshold function includes threshold values corresponding to the coefficients. A gain function is applied to each coefficient of the block to generate an excised block of coefficients. The gain function for each coefficient has a fixed-gain region for input values less than a corresponding threshold value from the threshold function, an excision region for input values greater than a predetermined multiple of the corresponding threshold value, and a soft

ATTORNEY DOCKET NO. TITAN-001XX
WEINGARTEN, SCHURGIN,
GAGNEBIN & HAYES, LLP
TEL. (617) 542-2290
FAX. (617) 451-0313

limiting region between the fixed-gain region and the excision region. The value of each coefficient is conditionally modified depending on which region it falls into. In particular, coefficients falling in the excision region are set equal to zero, while coefficients falling in the soft limiting region are multiplied by a value in inverse proportion to the coefficient value.

Once the excised blocks of coefficients have been generated, the inverse of the transform function is performed and an overlap-eliminating central portion of the inverse of the window function is applied to each excised block of signal samples.

A key feature of the excision technique is that it requires no synchronization or timing cues from the host receiver other than a commensurate rate sampling clock, and it necessitates no modification to the receiver's original demodulation logic. The latter is a serious problem for current state-of-the-art excision approaches, generally resulting in added cost, complexity and power consumption in the host radio's demodulation subsystem. Additionally, the technique requires only that each interfering source be narrowband relative to the bandwidth of the desired spread spectrum signal. The morphology-based calculation of the threshold function responds to geometric properties of the data and can easily distinguish anomalous features embedded in normal, or expected, backgrounds. The processing of overlapped blocks and the inverse windowing obviate any complicated and computationally costly adaptive demodulation methods that have been proposed in the literature, and which would serve to restrict the types of modulation that could be supported. Excision is effected using a mixed-mode thresholding strategy that allows the excision of strong interfering signals while applying softer limiting to those frequency components that exceed the threshold by lower margins.

ATTORNEY DOCKET NO. TITAN-001XX
WEINGARTEN, SCHURGIN,
GAGNEBIN & HAYES, LLP
TEL. (617) 542-2290
FAX. (617) 451-0313

Other aspects, features, and advantages of the present invention are disclosed in the detailed description that follows.

BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWING

The invention will be more fully understood by reference to the following Detailed Description in conjunction with the Drawing, of which:

Figure 1 is a general block diagram of a frequency-domain excision system as known in the art;

Figure 2 is a diagram illustrating block-based processing of a sampled communications signal in the system of Figure 1;

Figure 3 is a block diagram of a frequency-domain excision system in accordance with the present invention;

Figure 4 is a plot of a Blackman window function used in the excision system of Figure 3;

Figure 5 is a plot of an inverse Blackman window function used in the excision system of Figure 3;

Figure 6 is a diagram illustrating overlap-save excision processing used in the system of Figure 3;

Figure 7 shows superimposed plots of a baseband communications signal and an excision threshold function in the excision system of Figure 3;

Figure 8 is a plot of a non-linear gain function used in the excision system of Figure 3;

Figure 9 is a plot of input and output frequency spectra in the excision system of Figure 3; and

Figure 10 is a plot of the output signal-to-noise ratio of the excision system of Figure 3 as a function of the number of narrowband interfering signals.

DETAILED DESCRIPTION OF THE INVENTION

Figure 1 shows the basic components of a classical frequency domain excision system. As described above, excision processing generally begins with a Fourier transform 10 (such as

ATTORNEY DOCKET NO. TITAN-001XX
WEINGARTEN, SCHURGIN,
GAGNEBIN & HAYES, LLP
TEL. (617) 542-2290
FAX. (617) 451-0313

the FFT) to convert a block of input time waveform into the frequency domain. Once the frequency domain representation has been generated, the locations of the interfering signals are determined, generally by identifying anomalous peaks in the Fourier spectrum. Non-linear processing 12 is performed on the spectral coefficients to suppress the effects of unwanted narrowband signals. The modified frequency domain coefficients are then transformed back to the time domain using an inverse Fourier transform 14 in order to construct the output signal.

As shown in Figure 2, the Fourier transform typically operates on finite length blocks of successive samples of the input signal. In the most basic implementation of a frequency domain excision system, the continuous input sequence is divided into contiguous blocks of N samples each. The processing of Figure 1 is performed separately and independently on each such input block, producing an N-sample output block. Successive output blocks are then concatenated to form a continuous output sequence.

As mentioned above, one limitation of the processing depicted in Figure 2 is that a narrowband interfering signal may appear in more than one FFT coefficient, or frequency bin, despite the fact that the actual frequency of the interfering signal may be localized to a single bin. As described below, this problem is addressed in the disclosed excision system by the use of overlap-save processing.

Figure 3 shows an improved excision processing system. An input time-domain baseband signal is applied to window processing 16, and the windowed data is converted to the frequency domain by overlapped FFT processing 18. The frequency domain data, or spectral coefficients, from the FFT processing 18 are supplied to adaptive non-linear threshold formation processing 20 and non-linear gain processing 22. The threshold formation processing 20 calculates a set of threshold values that is used by the gain processing 22 to effect excision. The excised output data is

ATTORNEY DOCKET NO. TITAN-001XX
WEINGARTEN, SCHURGIN,
GAGNEBIN & HAYES, LLP
TEL. (617) 542-2290
FAX. (617) 451-0313

supplied to convolution processing 24 for purposes of smoothing. The output data then is converted back to the time domain by overlapped inverse FFT processing 26 and inverse window processing 28.

Figure 4 shows the Blackman window function (in normalized form) applied by the window processing 16. The general characteristic is a smooth, symmetric curve having a maximum at its midpoint and diminishing to zero at its end points. As described above, the use of this window provides for suppression of undesirable FFT sidelobes.

Figure 5 shows the inverse window function applied in the inverse window processing 28. Although this function goes to infinity at its endpoints, only the central 50% of the function is actually employed, as described in more detail below. Consequently, the gain provided by this function varies from 1 at the midpoint to about 3 at the endpoints.

Figure 6 illustrates the overall form of processing in the system of Figure 3, which is called overlap-save processing. In the overlap-save method, each input sample is processed twice. A block of N successive samples is processed to yield N/2 output samples. The second half of the same N-point input block is then concatenated with the first half of the next N-point input block for the processing that yields the next N/2 output points. Note that all input blocks are of length N, and they are overlapped by 50%. All output blocks are of length N/2, corresponding to the central portion of the N-point inverse FFT (IFFT) processing 26. The half-length output blocks are concatenated to form a continuous output sequence. Overlap factors other than 50% are possible and may offer advantages in special applications. In general, overlap factors in the range from 25% to 75% are desirable. The use of overlap-save processing enables those portions of the inverse-windowed IFFT output that are near the edges to be discarded, and only the central portions to be used. A continuous output signal is produced by sequentially selecting

ATTORNEY DOCKET NO. TITAN-001XX
WEINGARTEN, SCHURGIN,
GAGNEBIN & HAYES, LLP
TEL. (617) 542-2290
FAX. (617) 451-0313

the central regions of successive overlapped output records. The result of this processing is elimination of the input windowing effect on the output signal, and consequently elimination of the need for more complex demodulation methods.

More particularly, the first step in the processing consists of selecting a contiguous block of N input samples (baseband, complex) of the received signal. Next, the N-sample block is multiplied by an N-point window in order to minimize frequency domain sidelobes. Experiments were conducted using the Blackman window function of Figure 4. The windowed data is then converted into the frequency domain using an N-point complex FFT 18. The processing is overlapped in time as shown in Figure 6, using a 50% overlap factor. All blocks are processed identically.

Values of N as low as 128 and as high as 2048 have been used in simulation experiments. In general, higher values of N yield greater performance, albeit with a requirement for greater processing power. Systems using values as high as 2048 or 4096 may be feasible in the not too distant future.

Adaptive frequency domain threshold processing 20 (Figure 3) is realized using a non-linear morphology-based technique. The preferred approach produces excellent spectral estimates even with large numbers of closely spaced narrowband interferers, and it does so using simple and easy-to-implement calculations. Frequency domain threshold functions are computed independently for each N-sample block of data, thereby allowing the system to respond rapidly to the appearance of new interfering signals or the disappearance of old ones, and to other changes in the signal and/or interference environments.

Details of the computation are described below, using the following notation:

a. R(n,k) is the n^{th} value of an N-point sequence in the k^{th} data block .

ATTORNEY DOCKET NO. TITAN-001XX
WEINGARTEN, SCHURGIN,
GAGNEBIN & HAYES, LLP
TEL. (617) 542-2290
FAX. (617) 451-0313

b. $\max(R(p):R(p\pm Q))$ means the largest value in the $(Q+1)$-point subsequence of R between the indices p and $p\pm Q$, inclusive. $\min(R(p):R(p\pm Q))$ means the smallest value in the same subsequence of points.

c. $(n\pm B)_N$ means the addition/subtraction is to be performed modulo-N. This has the effect of treating all N-point sequences as circular.

Threshold formation consists of the following steps, in sequence:

1. The complex FFT outputs $X(n,k)+jY(n,k)$ are converted to magnitude format $M(n,k)$, where $M(n,k) = \mathrm{sqrt}(X(n,k)^2 + Y(n,k)^2)$. This yields an N-point array of real values.

2. A grayscale "closing" is performed on $M(n,k)$ using a kernel of length C, where C is an odd number:

   $Z1(n) = \max(M((n-(C-1)/2)_N,k): M((n+(C-1)/2)_N,k))$, followed by

   $Z2(n) = \min(Z1((n-(C-1)/2)_N,k): Z1((n+(C-1)/2)_N,k))$

3. A grayscale "opening" is performed on the data generated by the closing, using an odd-length kernel of length L:

   $Z3(n) = \min(Z2((n-(L-1)/2)_N,k): Z2((n+(L-1)/2)_N,k))$, followed by

   $Z4(n) = \max(Z3((n-(L-1)/2)_N,k): Z3((n+(L-1)/2)_N,k))$

4. Threshold functions derived from successive blocks of data are averaged together with exponentially decaying memory using a simple one-pole recursive digital filter:

   $T(n,k) = A\times T(n,k-1) + (1-A)\times B\times Z_4(n,k)$

There are five parameters in the above algorithm, namely N, C, L, A and B. Experiments have been conducted with N=1024. Values of C and L that have been found to work well with 1024-point sequences are 5 and 51, respectively. In general, the size

ATTORNEY DOCKET NO. TITAN-001XX
WEINGARTEN, SCHURGIN,
GAGNEBIN & HAYES, LLP
TEL. (617) 542-2290
FAX. (617) 451-0313

of the first kernel C is chosen to correspond to the expected bandwidth of relatively isolated narrowband interferers, whereas the size of the second kernel L is chosen to correspond to the expected bandwidth of groups of closely-spaced interferers that might exist. "B" is a scale factor which has been selected to be 2.5. "A" is a smoothing parameter which is positive and less than unity ($0 = A < 1$). It can be set to zero, in which case there is no block-to-block smoothing. That is, each block is determined independently of each other, and $T(n,k) = B \times Z_4(n,k)$. $A = 0.9$ represents a generally reasonable choice.

Figure 7 shows a frequency domain plot of a spread spectrum signal received at 0 dB SNR, in the presence of 50 interfering narrowband signals of random frequencies and amplitudes. Superimposed on the plot is a trace indicating the threshold function as derived from the above-described procedure. As shown, the threshold function closely follows the peak of the desired spread-spectrum signal and resides well below the amplitudes of most of the interfering signals.

The threshold function produced by this procedure represents an estimate of the basic signal spectrum (or the noise spectrum, if the signal is below the noise). The only assumption built into the morphology-based estimator is that the N-point spectrum of the desired signal has the appearance of colored noise with a smoothly varying envelope as a function of frequency. This is a characteristic property of any well-designed spread spectrum signal, or of a spread spectrum signal plus receiver noise, or of noise alone.

Figure 8 shows the gain function used in the non-linear gain processing 22 of Figure 3. Excision is accomplished by adjusting the amplitudes of the spectral coefficients in accordance with this non-linear function. The gain adjustment is made independently in every block and in each frequency bin within a block. As shown, the values on the input axis are normalized to the threshold value for the frequency bin as provided by the

threshold formation processing 20. Thus, if the signal value in a given frequency bin is less than the threshold for that bin, the signal receives unity gain. Otherwise, the signal value is modified in accordance with the portion of the gain curve to the right of the threshold value in Figure 8. For values between the threshold and about two times the threshold, the signal value is reduced by a generally decreasing amount as shown, and greater signal values are reduced to zero. This operation effects soft limiting on those signal bins that exceed the threshold by small amounts, and total annihilation of those signal bins that exceed it by greater amounts. Other gain functions having these general characteristics can also be used. The following exact function, which attenuates to zero all inputs that exceed the threshold by more than a factor of two, has been used in simulations:

$$g(n,k) = 1 - \min(1, \max(0, ((M(n,k)/T(n,k)) - 1)^2))$$

As a final step in the frequency domain processing chain, the frequency extent of the applied attenuation is broadened by the convolution operation 24 (Figure 3). The function $1-g(n,k)$ is convolved with a spreading function to reduce the effect of the excision operation on the reconstructed time sequence. In particular, the use of the spreading function reduces the time extent of distortion introduced by the excision. The three point spreading sequence $S = \{1/2, 1, 1/2\}$ has been used in experiments. The resultant overall gain factor which is applied to the complex FFT coefficients is given by

$$G(n,k) = \max(0, (1/2)\times g(n-1,k)_N + g(n,k) + (1/2)\times g(n+1,k)_N - 1)$$

Application of this gain factor to the FFT coefficients produces the k^{th} block of N complex output points of the frequency domain processing (Figure 3), *i.e.*,

$$Z(n,k) = G(n,k)\times(X(n,k) + jY(n,k))$$

ATTORNEY DOCKET NO. TITAN-001XX
WEINGARTEN, SCHURGIN,
GAGNEBIN & HAYES, LLP
TEL. (617) 542-2290
FAX. (617) 451-0313

The resulting frequency domain sequence is then transformed back into the time domain via the N-point inverse Fourier Transform processing 26.

As described earlier, because of the input windowing 16 the output of the IFFT processing 26 exhibits a time-varying amplitude modulation which can be detrimental to the performance of downstream demodulation and processing operations. A significant improvement is achieved by combining inverse windowing processing 28 with the overlap-save transform approach. Inverse windowing is performed by multiplying the complex output data produced by the IFFT 26 by the function 1/W(n). The complementary Blackman window W(m) and inverse Blackman window 1/W(n) are shown in Figures 4 and 5 respectively. In general, the application of an inverse window following the IFFT 26 could introduce noise and interference energy at and near the edges of the data record, since the windows themselves tend to zero at the end points (Figure 4). However, an inverse window is well-behaved near the center of the record, as shown in Figure 5, and therefore can be utilized with overlap-save processing without these deleterious effects.

It can be shown theoretically that the overall transfer function of the disclosed excision system is identically unity in the absence of any frequency domain excision action, assuming reasonable arithmetic precision (e.g., floating point) in its implementation. In other words, modification of the desired signal occurs only when spectral components are excised, and these modifications are focused entirely on the excised frequencies. The net result is a universal excision technique which imposes minimal distortion on the desired signal, needs no synchronization or timing cues from the host receiver other than a commensurate rate sampling clock, and which requires no modification to the receiver’s original demodulation logic. The excision system can be considered to be a pure appliqué, because

ATTORNEY DOCKET NO. TITAN-001XX
WEINGARTEN, SCHURGIN,
GAGNEBIN & HAYES, LLP
TEL. (617) 542-2290
FAX. (617) 451-0313

it operates independently of the demodulator. It is inherently compatible with virtually any digital modulation scheme.

In order to assess its performance, the above-described excision system was inserted into an end-to-end MATLAB simulation of a spread-spectrum radio with 21 dB of spreading gain. Figures 9 and 10 show relevant performance results of these simulations.

Figure 9 shows a plot of an input signal and the resulting excision output signal. The input signal is received at 0 dB SNR and includes 50 interfering narrowband signals at randomly selected frequencies and amplitudes. The horizontal axis indicates frequency bin number, from 1 to 1024. The vertical axis is labeled in dB. It will be observed that the output excision output approximates the spectrum of the input spread spectrum signal plus a small amount of additive white Gaussian noise, at 0 dB SNR. The droop observed at the band edges results from an input band-limiting filter in the receiver (not shown), whose bandwidth is matched to that of the desired signal.

Figure 10 shows the overall performance of the excision sub-system when installed in the aforementioned spread spectrum radio having 21 dB of processing gain, as a function of the number of interfering signals present in the band of the desired signal. Experiments were run at 0 dB and -10 dB input SNR at the receiver. Each trial used a different, randomly selected set of interfering signals having random frequencies and amplitudes. The amplitudes of the interfering signals varied over a 60 dB range, and included signals less than the excision threshold as well as signals exceeding it by as much as 50 dB. The curves of Figure 10 indicate graceful degradation of performance as a function of number of interfering signals present, for up to 100 simultaneous interfering signals in the band of the signal.

Other beneficial aspects of the disclosed system include the following:

1. Large numbers (e.g., 20-100) of narrowband interfering signals can be handled and excised simultaneously.

ATTORNEY DOCKET NO. TITAN-001XX
WEINGARTEN, SCHURGIN,
GAGNEBIN & HAYES, LLP
TEL. (617) 542-2290
FAX. (617) 451-0313

2. Excision performance is independent of the frequencies of the interference. Interfering sources may be centered at arbitrary or random frequencies in the band of the desired spread spectrum signal, and simultaneous interfering sources may have substantially different amplitudes, e.g., spanning a dynamic range of 50 dB or more.

3. In the absence of interfering signals, the excision system introduces virtually no change to the received signal. Distortion or modification of the desired waveform is essentially zero at frequencies other than those at which interfering signals exist.

4. The excision system is adaptive and responds rapidly to changes in the RF environment.

5. Frequencies and amplitudes of interfering sources are determined implicitly as part of the excision control logic, and this information can be made available for communication to other equipment for various purposes. For example, this information can be supplied to remote transmitters to support adaptive transmission strategies to avoid occupied spectral regions.

6. The excision methodology is independent of the details of the spread spectrum signaling waveform; it requires no knowledge of waveform parameters. It can therefore be implemented as a universal appliqué, and incorporated as a tandem module into a spread spectrum receiver without modification.

It will be apparent to those skilled in the art that other modifications to and variations of the disclosed system and methods are possible without departing from the inventive concepts disclosed herein, and therefore the invention should not be viewed as limited except to the full scope and spirit of the appended claims.

ATTORNEY DOCKET NO. TITAN-001XX
WEINGARTEN, SCHURGIN,
GAGNEBIN & HAYES, LLP
TEL. (617) 542-2290
FAX. (617) 451-0313